Retroreflector diffraction modeling

S. Loiseau, S. Shaklan, D. Redding, E. Schmidtlin

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA, 91109-8099

ABSTRACT

The SIM metrology subsystem utilizes cornercube retroreflectors as fiducials. These components will introduce errors in the metrology output that must be quantified. Eventually, a complete modeling of the metrology subsystem will be needed. For that purpose, we are developing an optical model for a cornercube retroreflector, taking into account most of the defects present in such an optical part. Our goal is to give a phase map of the wavefront produced by the interference of the reference beam and the metrology beam (which suffered multiple reflections during its round-trip between the cornercubes). Our first step towards this goal is the construction of an optical model and its validation, using the MACOS and VSIM packages.

Keywords: Retroreflectors, diffraction, aberrations, metrology, interferometry, astrometry

1. INTRODUCTION

The Space Interferometry Mission (SIM)[1] is a space-based interferometer dedicated to very accurate narrow and wide–angle astrometry. It comprises four interferometers sharing a common baseline whose length must be monitored to an extremely high precision by means of a heterodyne metrology subsystem. The latter uses interferences between frequency-shifted polarized laser beams to monitor the displacements of the fiducial points of the baseline. These fiducial points are triple cornercube retroreflectors (a.k.a. triple cornercubes). A one-dimensional metrology experiment is being performed at JPL in order to prove that the desired accuracy is indeed reachable. This experiment is part of the Micro-Arcsecond Metrology Testbed (MAM),[2] one of several testbeds being developed for SIM. For a more complete description of the design of the SIM instrument, the reader is referred to other papers in these proceedings.[3]

2. CORNERCUBES: PROPERTIES AND PROBLEMS

In this section, we give a general idea of the properties and defects of a cornercube. A cornercube is an assembly of three flat mirrors, forming a cube corner – so why cornercube and not cubecorner ? a question we will leave open – . Its essential property is to reflect a ray of light towards its incident direction (see figure 1).

Thus, an observer looking at a cornercube from any viewing angle, will always see his own eye around the vertex of the retroreflector (the common point between the three surfaces). Although a cornercube may look quite perfect to the untrained eye, it carries, as any optical part, its share of defects:

1. When two surfaces are assembled, especially at right angle to each other, the contact is less than perfect: there is a gap, due to the glue, between them. These gaps are probably of the order of 25 to 100 μm.

2. The edge of the flat surfaces, close to the virtual vertex, are not perfectly orthogonal: there is a bevel. We usually include the bevel in the gap error.

3. The flat surfaces are not perfectly perpendicular by pairs: there is a dihedral error, of the order of one arcsecond, for good cornercubes.

4. Each surface is not perfectly flat. For superpolished mirrors, we can expect a surface error of $\lambda/100$ rms.

5. For the triple cornercube,[4] the common vertex is not really common: each single cornercube has its own vertex and the error we are aiming at with regard to this assembling problem is of the order of 1 μm.

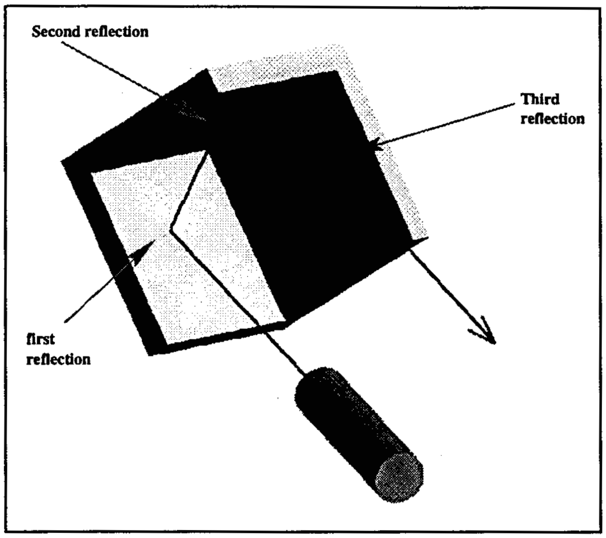

Figure 1. An ordinary reflection on a cornercube retroreflector.

Theses defects are summarized in figure 2 where the assembly of two flat mirrors is represented.

The effects of these imperfections are not yet fully understood, especially since the level of precision required on the metrology is extremely high. The first question is whether the shape of the reflected beam will still be Gaussian, and how badly aberrated it will be. Once this is quantified, we will be concerned with the effects of the aberrated wavefront on the metrology measurement. It is possible that these effects would not appear until a high degree of precision is sought for.

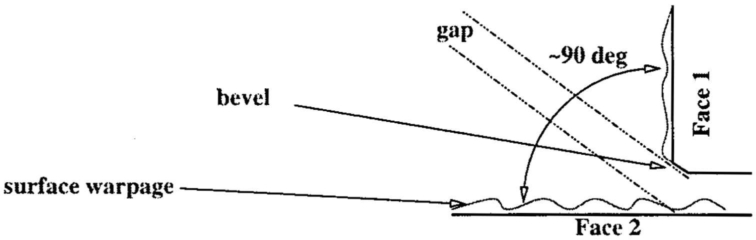

Figure 2. Defects encountered when two flat surfaces are glued together at a right angle, i.e. defects found on a cornercube retroreflector.

3. OBJECTIVES

Reduced to its simplest expression, a metrology subsystem consists of two retroreflectors, a laser source and a detector[5,6]: the trick is to measure accurately the distance between the fiducial points, i.e. the vertices of the cornercubes, by measuring an interferometric signal produced by the recombination of the reflected wavefronts from the cornercubes. These wavefronts are distorted by the reflections and we are interested in knowing how they are distorted, the amount of distortion and the resulting error on our metrology measurement. These are the ultimate objectives of this work, performed at JPL, by members of the Micro-Arcsecond Metrology Testbed, a testbed for the Space Interferometry Mission.

Our first intermediate stop, on our way to the ultimate goal, is the construction of a cornercube optical model and its validation. The optical model is being built in MACOS (Modeling and Analysis for Controlled Optical Systems), a package developed at JPL by Dave Redding *et al.*,[7] dedicated to fast, accurate and detailed optical models. MACOS has a full diffraction propagation capability combined with ray-trace and differential ray-trace.

The work described in this paper follows these guidelines:

- Create a MACOS prescription for a cornercube, with a number of free parameters that will be varied for coarse and fine tuning.
- Build an experimental setup and measure real diffraction patterns from cornercubes.
- Compare the data and the simulation results and adjust the MACOS prescription in consequence.
- Characterize the present effects.

4. AN OPTICAL PRESCRIPTION

Building a cornercube with MACOS seems easy but may be tricky. In essence, it is the assembly of three non-sequential flat surfaces, set at 90° from each other. Since MACOS performs differential ray-tracing, one must take care not to send the chief ray directly to the vertex of the retroreflector, where it could become undefined.

The parameters which are free to be varied in the prescriptions are:

- Positions (x,y,z) of the optical surfaces.
- Diffraction propagation distance.
- Zernike coefficients on each optical surface.
- Width of the gaps between the surfaces of the cornercube.
- Tilts of these surfaces, i.e. angle between them.

The prescription comprises reference surfaces used to propagate diffraction: diffraction is first propagated from a plane corresponding to the diaphragm (see section 5 below) to the cornercube and back to the focal plane. The diffraction propagator is a near-field (Fresnel) plane-to-plane propagator. Once gaps are introduced between the faces of the cornercube, MACOS produces diffraction such as the one shown on figure 3.

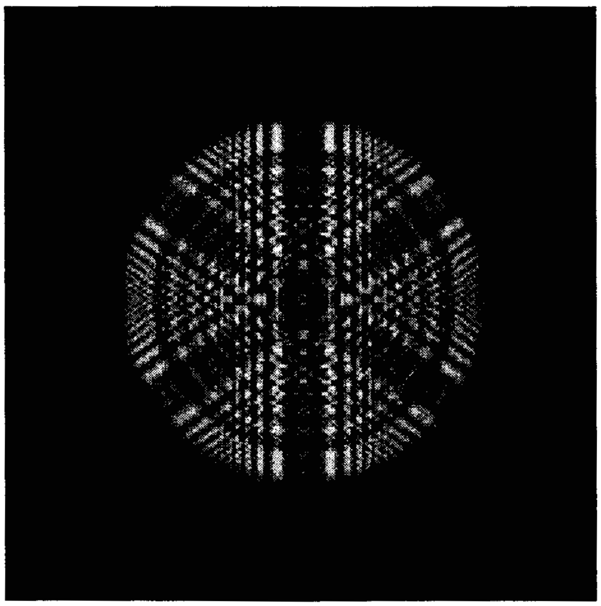

Figure 3. A diffraction pattern for an imperfect cornercube obtained with MACOS. The diameter of the beam is 5 millimeters.

This image corresponds to a short propagation distance and the effects of the gaps can clearly be seen. Dihedral errors and surface figures have not been introduced for this image. The high versatility of MACOS has its drawbacks: there are lots of free parameters. For instance, an obscuration (simulating the gap between two surfaces) is defined by 4 parameters, any of which can be varied. We will come back to that in the following sections.

5. EXPERIMENTAL SETUP

Our first experimental setup is rather simple and aimed at analyzing the patterns produced with a uniform beam, not a Gaussian beam. The reasons for that are as follows: first, before getting into more complicated assumptions, we wanted to analyze a simple case, hence the choice of a top-hat beam; second, MACOS is undergoing some changes and it appeared that Gaussian beam propagation was not being handled properly; we expect this to be fixed very soon and will then use an unaltered laser beam for the experiment. The layout of the setup is shown on figure 4.

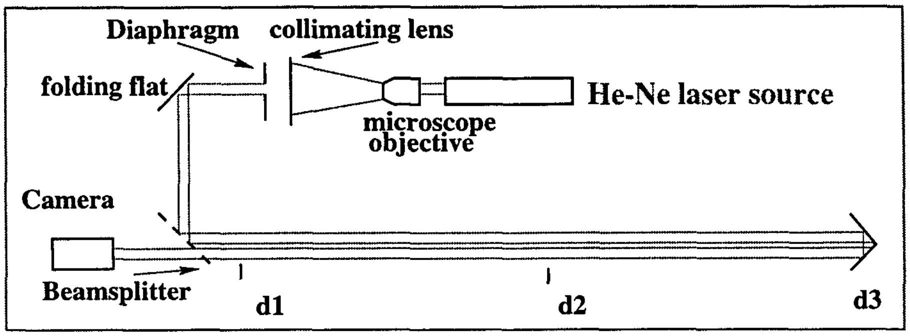

Figure 4. The experimental setup. d1, d2 and d3 are the three possible positions of the analyzed retroreflectors (or reference flat mirror) for which we recorder data.

The microscope objective plus the collimating lens and the diaphragm create a top hat beam of acceptable shape. The beam is then propagated to the reflecting surface through a beamsplitter and back to a camera. We used 4 different reflecting surfaces: a reference flat, used mainly to calibrate the aberrations of the naked beam, and three different cornercubes of varied quality. The purpose of this maneuver was to apply the aberrations found with the reference flat and use them as inputs for the cornercube solution.

The camera is a Pulnix TM 7CN, which has an array of 768×494 rectangular ($8.4 \times 9.8\,\mu$m) pixels. The frame grabber produces 640×480 images with an equivalent square pixel size of $10.08\,\mu$m. The quality of the data recording system (camera + frame grabber) is degraded by an unwanted reflection on the camera window, which produced sets of high-spatial frequency oblique fringes on the data, later filtered out but which nonetheless decreased the general quality of the images. Also, the dynamic range of the camera (8 bits) and the absence if proper filters contributed to a lower quality of images. Typical images obtained with our experiment are shown later on.

6. COMPARING DATA AND SIMULATIONS

We need to compare the data and the results of our simulations in a least-squares sense (i.e. minimize the square of the difference between the values of each pixel, over the whole image), adjust the MACOS prescription and reiterate. The adjustments concern all the parameters which are free to vary. This operation would be very fastidious if performed by hand. We use another JPL developed software, VSIM, which serves as an interface between MACOS, the data and a least-squares solver, NPSOL (see figure 5). VSIM is driven by a configuration file, which tells it how many experimental images to load, which optical prescription to consider, as well as which parameters to vary, iteration after iteration. The free parameters comprise those given in section 4 plus the basic image parameters: background level, total flux and position of the central pixel. Several other *ad hoc* parameters were introduced in the process, such as the clock angle of the cornercube and the decenter of the beam with respect to the vertex of the cornercube.

Because of the high number of parameters for which we are trying to solve, the risk of getting VSIM stuck in a local minimum of the chi-square function is high. Indeed, we managed to achieve acceptable figures-of-merit for

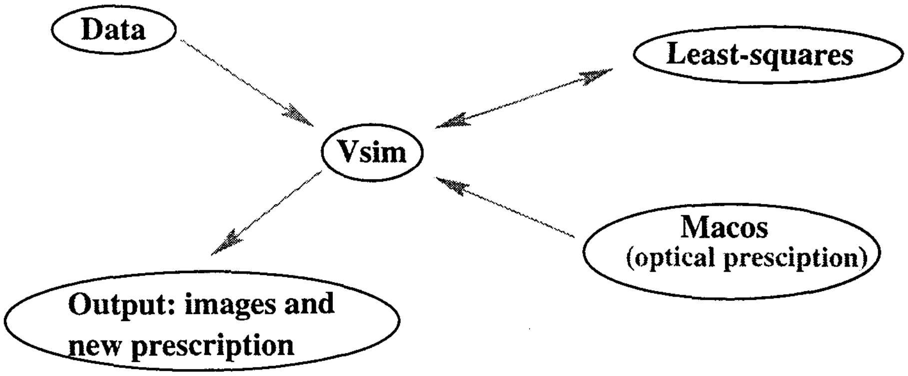

Figure 5. The algorithm of our task. Several images can be treated simultaneously so as to solve for parameters coherently over them.

simple cases, such as the reference flat one, but not for the cornercubes, even though the results may appear visually to be satisfying. On figure 6, we show an experimental diffraction pattern obtained for the flat reference surface and the simulated image, obtained with VSIM and our optical prescription. The figure–of–merit dropped to reasonable value, given the quality of the data. The aberrations found in the beam are defocus, spherical, a bit of astigmatism and very little coma (we considered only low-order Zernikes, so as to keep the computations simple).

Figure 7 shows the same type of comparison but for a flat mirror place further away, i.e. for a longer propagation distance. The figure of merit for this simulation was as good as for the d1 distance.

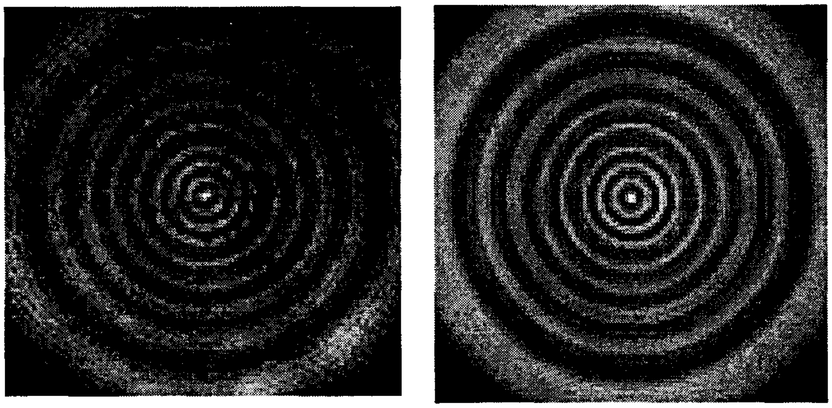

Figure 6. Comparison of data (left) and simulation (right): These images are the diffraction patterns obtained when a flat reference surface is positioned on d1 (see figure 4).

Finally, the results obtained for a cornercube are displayed on figure 8. Most of the main features of the image were indeed reproduced by our simulation. However, adjustments remain to be done: one of the tilts is wrong and leads to a badly placed gap diffraction pattern. Also, the width of the gaps are slightly incorrect. We do not report on the information from the simulation such as gap width or Zernike coefficients for each surface. This is a first step and the improvements to this work are being described in section 7.

7. ONGOING WORK AND CONCLUSIONS

Drawing the lessons from our first experiment, we are rebuilding a new setup with better optics and a new camera. The main feature of this new experiment will be the camera, which has a 1048×1048 array of $9\,\mu m$ pixels, is electrically cooled and has its own frame grabber. Moreover, two of our previous limiting factors, the dynamic range

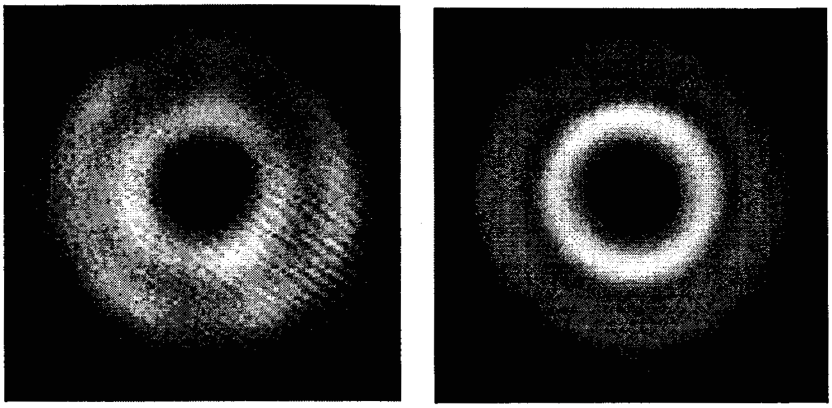

Figure 7. Comparison of data (left) and simulation (right) (2): the same reference surface is put at position d2 (see figure 4).

of the camera (8 bits) and the camera window are eliminated since this camera has a 12 bit dynamic range and no window. This will greatly enhance the quality of our data.

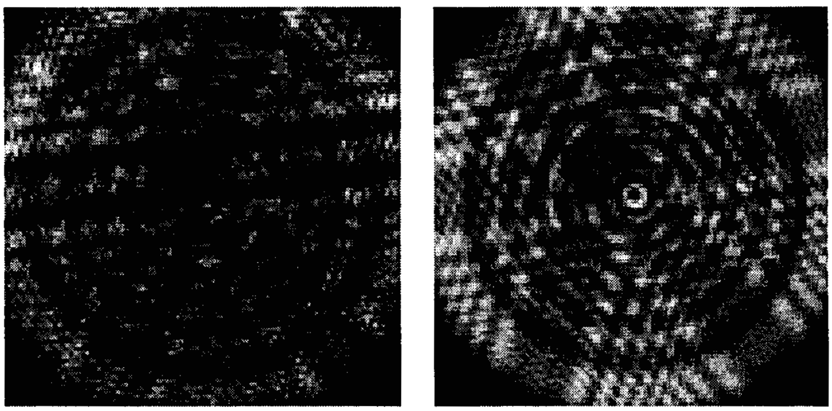

Figure 8. Comparison of data (left) and simulation (right) (3): These images are the diffraction patterns obtained for a cornercube placed at d1 (see figure 4).

We replaced the microscope objective – collimating lens device by a new beam expander, thus hoping to get a better quality beam. The folding flat and the beamsplitter have been changed as well for better parts. We are taking extra care in positioning the optics, especially the flat reference mirror and the cornercube, so as to remove one free parameters of the system: the exact diffraction propagation distance.

The purpose of this work is to predict the performance of the metrology system and thus of SIM. We are hoping to quantify some non-linear effects that may occur in the metrology output. This will help in redefining the error budget allocation for the metrology subsystem and will be an aid in the design of this very system. Moreover, it will be used for on–orbit calibration.

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